Structure of multimodal sensorimotor dependencies

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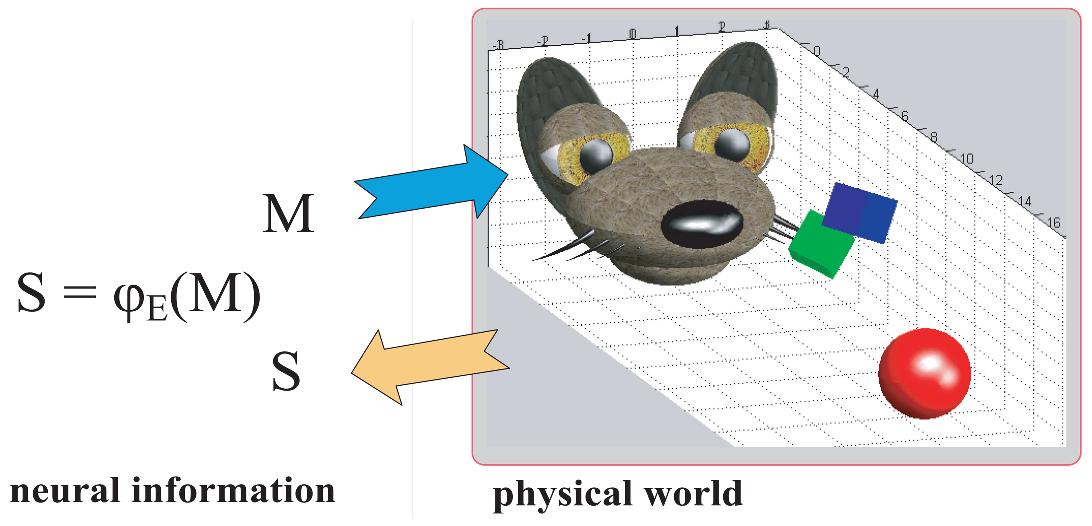
What can be understood of the world through sensorimotor contingencies ?



What is the kind of structure faced by nervous systems, or any embodied agent, in their interactions with the world ? How does this structure reflect the underlying physical world ?

Perception is commonly explained by a hard-wired interpretation of our sensory inputs:

« It was clear that the character of the sensation ([vision], touch, heat, or pain) depended upon the fibre carrying the message, not the nature of the message, since this consisted of trains of similar impulses in all fibres »

Barlow, Single units and sensation 1972

But this is only a partial answer, since it does not explain how this hard-wiring can arise at a phylogenetic scale, or even at an individual developmental scale (Hirsh ; Blakemore ; Sur). Neither does it provide an explanation for the complex reinterpretation observed in sensory substitution experiments (Bach-Y-Rita ; Epstein).
Finally, we can wonder if a hard-wired interpretation is any explanation at all from a philosophical point of view (O'Regan ; Noe ; Chalmers ; Gold).

The sensorimotor theory

« When we perceive before us objects distributed in space, this perception is the acknowledgment of a lawlike connexion between our movements and the therewith occurring sensations [...]. What we perceive directly is only this law »

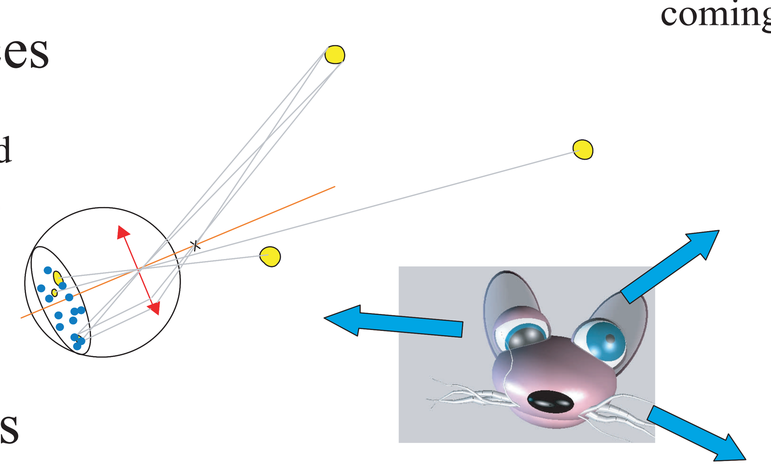
Helmoltz, The facts in perception

Embodied agents face a set of lawlike interactions, not an arbitrary set of diconnected measurements. This provides more structure to be theoretically studied than the usual structure considered when dealing with sensory inputs alone, and we claim that perception is the understanding of this structure.

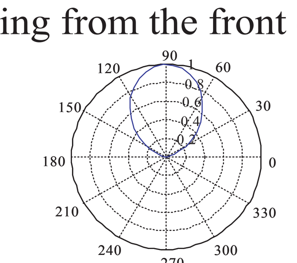
The simulated rat head

Sensory devices

randomly distributed photosensitive cells, optics, diaphragm

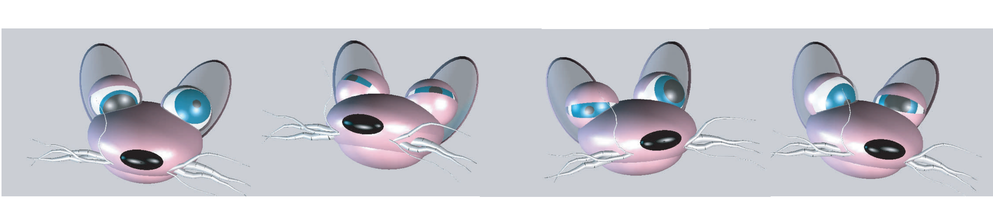


gain profile favoring sounds coming from the front of the ears



tactile devices stick to the sources they come into contact with.

Motor abilities



Intrinsic structure of the sensorimotors contingencies

Data of the problem :

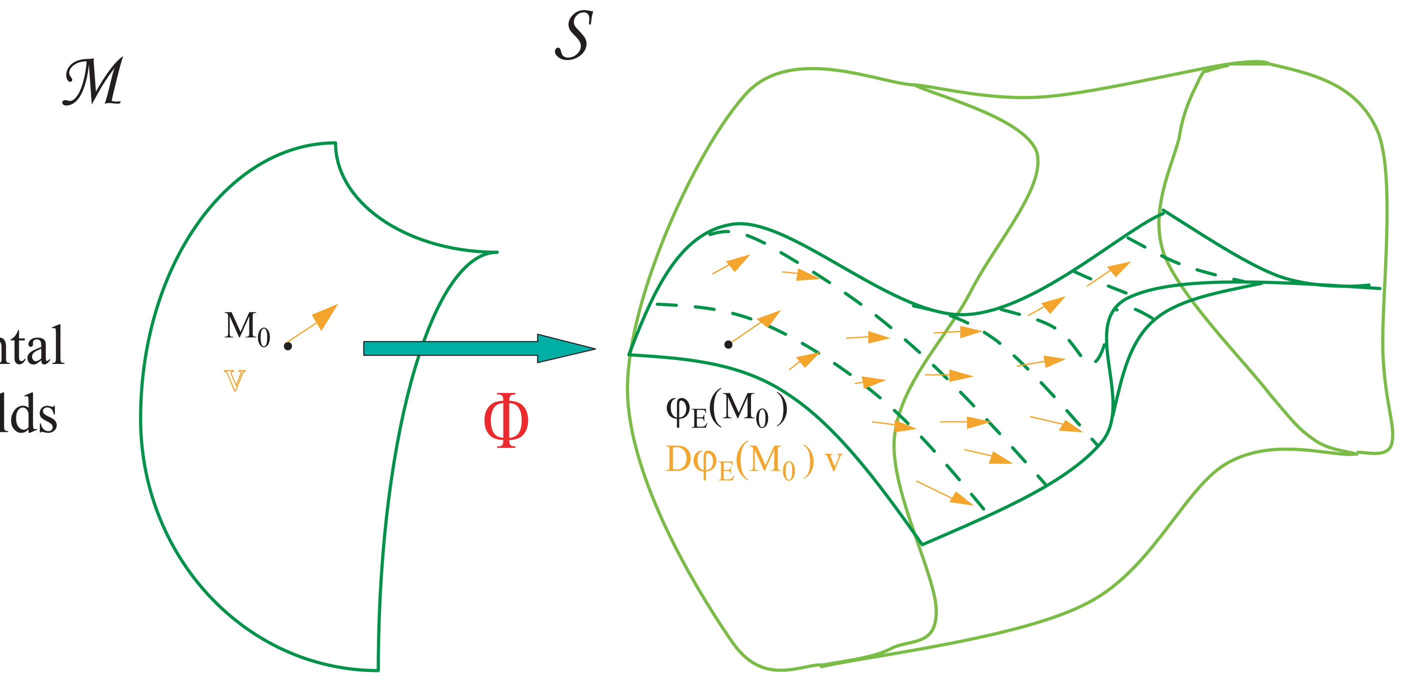
- sets of motor outputs $\mathcal{M}$ and sensory inputs $\mathcal{S}$
- set of sensorimotor contingencies : $\Phi = \{\varphi_E : \mathcal{M} \to \mathcal{S}\}$

What are we looking for ?

- information about the external world

$\to$ independent of the code : same for Φ and $f \circ \Phi \circ g$
where $f{:}\mathcal{S} \to \mathcal{S}'$ and $g{:}\mathcal{M}' \to \mathcal{M}$ are one-to-one changes of encoding

Fundamental vector fields



Part of answer : compensable transformations

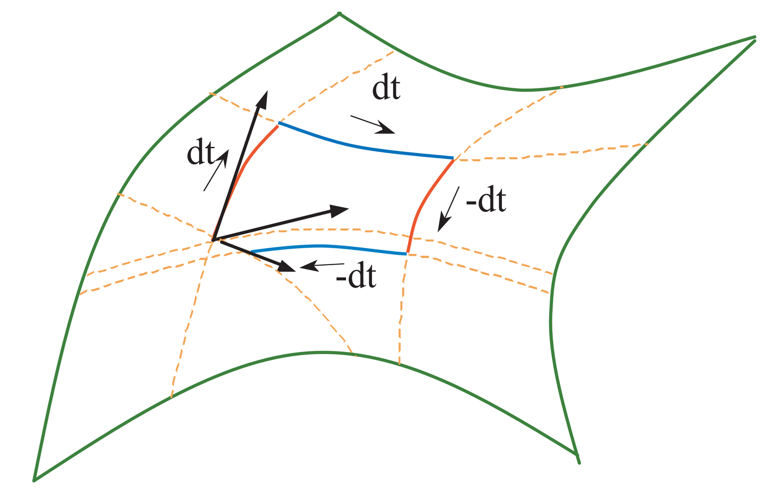
- $\Gamma(\Phi) = \{h : \mathcal{M} \to \mathcal{M} \,/\, \Phi \circ h = \Phi\}$
- Group, satisfying : $\Gamma(f \circ \Phi \circ g) = g^{-1} \circ \Gamma(\Phi) \circ g$

$\to$ its structure is invariant to sensorimotor changes of encoding
- action over the sensory inputs : choose M_0, define

$\mathcal{S}_{M_0} = \{\varphi_E(M_0),\ \varphi_E \in \Phi\}$ $\qquad \lambda : \Gamma(\Phi) \times \mathcal{S}_{M_0} \to \mathcal{S}_{M_0}$

$\qquad (h, \varphi_E(M_0)) \mapsto \varphi_E(h(M_0))$

Lie bracket & commutativity



An algorithm to understand the structure of $\Gamma(\Phi)$

Fundamental vector field

associated with a left-invariant vector field X on $\Gamma(\Phi)$ for the action λ :

$$X^{\mathcal{S}}(\varphi_E(M_0)) = \frac{d}{dt}\lambda(e^{-Xt}, \varphi_E(M_0))\Big|_{t=0} = \frac{d}{dt}\varphi_E(M_X(t))\Big|_{t=0}$$

with $M_X(t) = e^{-Xt}(M_0)$
If there is no singularity, only the tangent vector of $M_X(t)$ at $t=0$ is needed to compute the whole vector field.

Lie algebra of $\Gamma(\Phi)$

The Lie bracket can then be computed using a local linearization $\xi : \mathcal{S} \to R^S$ and the equation :

$$[X,Y] = \left(X_i \frac{\partial Y_j}{\partial \xi_i} - Y_i \frac{\partial X_j}{\partial \xi_i}\right) \frac{\partial}{\partial \xi_j}$$

The vector space of the fundamental vector fields with this Lie bracket is isomorphic to the Lie algebra of $\Gamma(\Phi)$.

Decomposition of the algebra

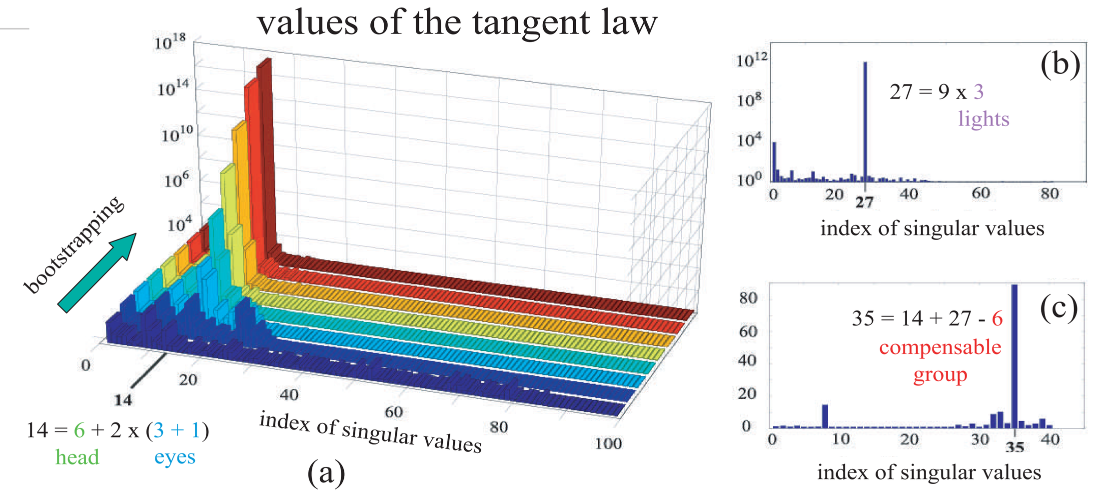
It can be shown that the vector fields related to the commutative transformations are the nullspace of the Killing form defined as :

$$K(X,Y) = tr([X,[Y,.]])$$

In the case of SE(3), a basis corresponding to a system of orthogonal translations and pure rotations arround these translations can be computed using linear algebra.

Estimation of tangent spaces and dimensions

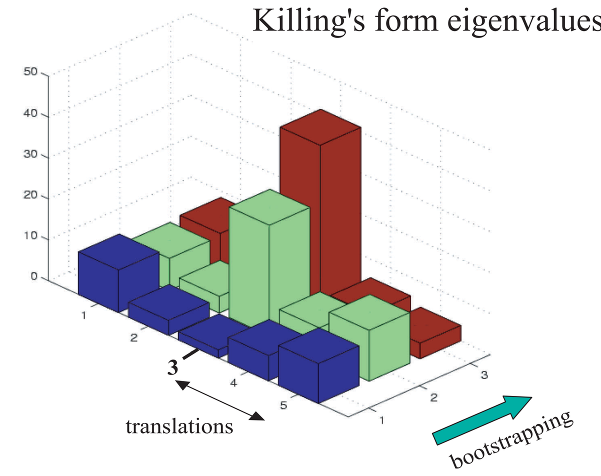
Ratio of the singular values of the tangent law



Steps of a bootstrapping procedure to estimate the amplitudes of the ratio of the successive singular values of the matrix constituted by a collection of tangent vectors observed :

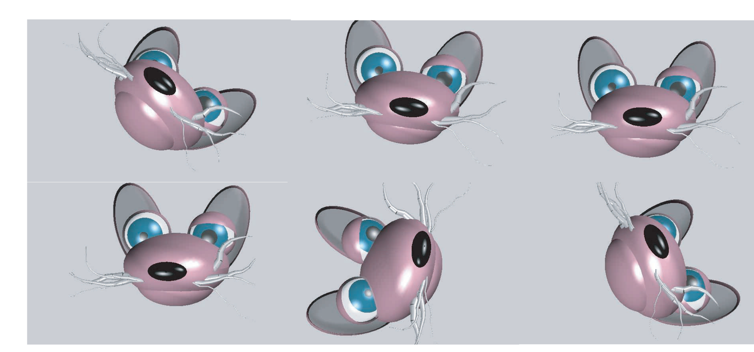
a) when moving in a fixed environment
b) for a given motor output but moving environment
c) changing motor output and moving environment

Killing's form eigenvalues



Ratio of the eigenvalues of the Killing form.

The nullspace gives the tangent vectors to commutative transformations.



Moving along 6 independent fundamental vector fields computed by the algorithm. The Lie bracket let the algorithm understand the commutativity of these movements.

Références

[1] D. Philipona, K. O'Regan, and J.-P. Nadal. Is there something out there ? Inferring space from sensorimotor dependencies. Neural Computation, 15(9), 2003.
[2] J. K. O'Regan and A. Noë. A sensorimotor account of vision and visual consciousness. Behavioral and Brain Sciences, 24(5):883–917, 2001.